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Procedia CIRP 56 (2016) 115 – 118

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9th International Conference on Digital Enterprise Technology - DET 2016 – "Intelligent Manufacturing in the Knowledge Economy Era

Effect of cutter runout on chatter stability of milling process

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Abstract

Chatter-free cutting parameter selection is a very important topic in milling process. Thus, numerous researches have been done to predict the stability lobes of milling process. Practical milling process is always influenced by multiple modes and cutter runout which may induce multiple delays. However, in most previous work conducted in time domain, stability lobes were traditionally predicted by only selecting the most flexible mode, which inevitably loses the accuracy in some speed ranges. Especially, combined effect of multiple modes and cutter runout makes stability analysis more difficult. To this end, this paper aims at revealing the influence of cutter runout on milling stability when multiple modes occur. Numerical and experimental studies are carried out to study this issue. Prediction algorithm is established by taking into account the physical status of process. Simulated and measured results confirm that the occurrence of cutter runout can locally increase the stable region, as shown in Fig. 2. Besides, numerical studies are also conducted to investigate the combined effects of feed rate, helix angle and cutter runout.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Chatter stability; Milling process; cutter runout

1. Introduction

Milling process has been extensively applied in die components, aeronautical, astronautical and automobile parts and other products in manufacturing industry. However, the occurrence of chatter vibration will lead to poor surface finish, rapid tool wear and even damage of machine tools. Therefore, chatter-free cutting parameter selection is a very heated issue in milling process, and has been attracting numerous researchers' attention. Altintas[1-3] have done very good work and pointed out that the wave shift of the adjacent cutting surfaces may give rise to the exponentially growing chip thickness and unstable cutting process, i.e., the well-known chip-regenerative chatter. Modeling of machining chatter has been a heated topic of vast amounts of studies in literature. Altintas and Budak[2] formulated the chip regeneration and developed a zero-order approximation (ZOA) method, which proved to be efficient and analytical in determining stability lobes from the frequency domain. Later, Merdal and Altintas[4] found that the ZOA method would fail in the case of low radial immersion, and a multi-frequency solution was proposed by considering not only the average but also several harmonics of directional coefficients to overcome this shortcoming.

In contrast, time domain simulation is more powerful in predicting the stability of milling process since the kinematics of milling process, cutting mechanism and cutter geometry are reflected. Among others, Mann and co-workers[5,6] proposed a temporal finite element analysis aiming to predict stability lobes. From a numerical viewpoint, Insperger et al.[7] proposed the so-called 'semi-discretization (SD) method', which was widely adopted by the following research work. Wan et al. [8]proposed an improved and unified SD method for milling process with multiple delays, and then they employed the method to thread milling[9] and multifunctional tools[10]. Similarly, Ding[11] proposed a full-discretization method. Then, Guo et al. [12] developed a third-order full-discretization method to enhance the convergence efficiency. However, the above work mainly focused on the stability lobe construction for the ideal cutting conditions, cutter runout influence combined with feed rates ,helical angle and multiple modes effect had rarely been investigated. In this paper, the

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.10.034

authors focused on revealing the influence of cutter runout combined with feed rates and helical angle on milling stability when multiple modes occur. Experimental work has been carried out as well.

Nomenclature

K_t , K_r	Tangential and radial cutting force coefficient
a_p	Axial depth of cut
$\varphi(i\omega_c)$	Transfer function of milling system
N	Number of cutting teeth
M	Modal mass matrix of milling system
C	Damping ratio matrix of milling system
K	Modal stiffness matrix of milling system
Q	Displacement of the cutter
τ	Time delay
ρ, λ	Runout offset and its orientation angle

2. Chatter prediction with multiple delays under multiple modes

2.1. Stability limit with multiple modes

In practical milling process, the milling system is always dominated by multiple modes. According to the authors' previous study[13], the stability boundary of multiple modes dominated system can be treated as a combination of the boundaries of each single-mode case. For the completeness of description, the theoretical proof is given in brief.

According to Ref.[1], the critical axial depth of cut $a_{\text{p,lim}}$ for chatter stability limit can be determined by

$$\begin{aligned} a_{\text{p,lim}} &= -\frac{2\pi\Lambda_R}{NK_t}(1+\kappa^2) \\ \kappa &= \Lambda_I / \Lambda_R \end{aligned} \tag{1}$$

where Λ_R and Λ_I are the real and imaginary parts of the eigenvalue of the following characteristic equation.

$$a_0\Lambda^2 + a_1\Lambda + 1 = 0 \tag{2}$$

where the variables have same meaning with the ones in Altintas' book[1]. By solving Eq.(2), we obtain:

$$\begin{aligned} \Lambda &= \frac{-1}{2\upsilon\varphi_{XX}(i\omega_c)\varphi_{YY}(i\omega_c)}\left(\begin{array}{l}\alpha_{XX}\varphi_{XX}(i\omega_c)+\alpha_{YY}\varphi_{YY}(i\omega_c) \\ \pm\sqrt{\begin{array}{l}(\alpha_{XX}\varphi_{XX}(i\omega_c)+\alpha_{YY}\varphi_{YY}(i\omega_c))^2 \\ -4\upsilon\varphi_{XX}(i\omega_c)\varphi_{YY}(i\omega_c)\end{array}}\end{array}\right) \\ \upsilon &= \alpha_{XX}\alpha_{YY} - \alpha_{XY}\alpha_{YX} \end{aligned} \tag{3}$$

Assuming that, the milling tool-spindle assembly is a symmetric system, i.e. $\varphi_{XX}(i\omega_c) = \varphi_{YY}(i\omega_c)$, and then Eq.(4) is obtained.

$$\begin{aligned} \Lambda &= \frac{\chi}{\varphi_{XX}(i\omega_c)} \\ \chi &= -\frac{\alpha_{XX}+\alpha_{YY} \pm \sqrt{\alpha_{XX}^2+\alpha_{YY}^2+2\alpha_{XX}\alpha_{YY}-4\upsilon}}{2\upsilon} \end{aligned} \tag{4}$$

Obviously, Λ directly varies with respect to $\varphi_{XX}(i\omega_c)$ as χ in Eq. (4) is a constant for a certain cutting condition. Actually, $\varphi_{XX}(i\omega_c)$ can be rearranged as follows.

$$\begin{aligned} \varphi_{XX}(i\omega_c) &= \sum_{j=1}^{N_m} \frac{1}{-m_{X,j}\omega_c^2 + 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i + m_{X,j}\omega_{X,j}^2} \\ &= \sum_{j=1}^{N_m} \frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2) - 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^4+\omega_c^4) - 2m_{X,j}^2\omega_{X,j}^2\omega_c^2 + 4\xi_{X,j}^2\omega_{X,j}^2 m_{X,j}^2\omega_c^2} \end{aligned} \tag{5}$$

Generally, $\xi_{X,j}$ is very small for a metal structure. Hence, $4\xi_{X,j}^2\omega_{X,j}^2 m_{X,j}^2\omega_c^2$ can be dropped from the denominator, i.e.

$$\varphi_{XX}(i\omega_c) \approx \sum_{j=1}^{N_m} \frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2) - 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \tag{6}$$

Since the chatter frequency ω_c is around natural frequency of some certain mode $\omega_{X,j}$, we obtain the following equation:

$$\begin{aligned} &\frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2) - 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \gg \\ &\sum_{\varsigma=1,\varsigma\neq j}^{N_m} \frac{m_{X,\varsigma}(\omega_{X,\varsigma}^2-\omega_c^2) - 2\xi_{X,\varsigma}\omega_{X,\varsigma}m_{X,\varsigma}\omega_c i}{m_{X,\varsigma}^2(\omega_{X,\varsigma}^2-\omega_c^2)^2} \end{aligned} \tag{7}$$

According to Eq.(7), Eq.(6) can be approximated as:

$$\varphi_{XX}(i\omega_c) \approx \frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2) - 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2} \tag{8}$$

Then, the following equation is obtained,

$$\begin{aligned} \Lambda &= \frac{\chi}{\varphi_{XX}(i\omega_c)} \\ &= \chi\frac{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2}{m_{X,j}(\omega_{X,j}^2-\omega_c^2) - 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i} \\ &= \chi m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2 \frac{m_{X,j}(\omega_{X,j}^2-\omega_c^2) + 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i}{m_{X,j}^2(\omega_{X,j}^2-\omega_c^2)^2 + 4\xi_{X,j}^2\omega_{X,j}^2 m_{X,j}^2\omega_c^2} \end{aligned} \tag{9}$$

Combining Eq. (9) with Eq. (6) yields

$$\begin{aligned} \Lambda &\approx \chi[m_{X,j}(\omega_{X,j}^2-\omega_c^2) + 2\xi_{X,j}\omega_{X,j}m_{X,j}\omega_c i] \\ &= \frac{\chi}{\varphi_{XX,j}(i\omega_c)} \end{aligned} \tag{10}$$

Because the limit axial depth of cut is determined by Λ, and Λ is proportional to the jth mode term $1/\varphi_{XX,j}(i\omega_c)$, that is to say, the limit axial depth for multiple mode case can be approximated as the one obtained by the selected single mode case. In other word, the stability lobes directly obtained from multiple modes can be approximated by the combined envelop of the stability lobes corresponding to different vibration modes. With this conclusion, a multiple modes problem can be simplified as the combination of some single mode cases.

In the above part, the modal interactions of the cutter are well investigated. Similar results can also be introduced to low rigid workpiece milling process. According to Ref [14], the limit depth of cut considering low rigid workpiece can be obtained as:

$$a_{\mathrm{p,lim}} = \frac{1}{(N/2\pi)\alpha_{xx}K_{\mathrm{t}}\mathrm{Real}[\varphi_{\mathrm{xx}}(\mathrm{i}\omega_c)]} \tag{11}$$

In Eq.(11), function "Real []" means the real part the transfer function of structure. From Eq.(11), it is obvious that the limit depth of cut is proportional to $1/\varphi_{\mathrm{XX}}(i\omega_{\mathrm{c}})$, which is similar to Eq.(4). So the relationship for multiple modes and single modes case can be analyzed in the same way as the tool. Therefore, the same concept of above lowest envelop method can also be introduced to the low rigid workpiece milling process, same to the conclusion of Ref.[14].

2.2. Chatter prediction with multiple delays

An actual milling system is always dominated by multiple delays, which is usually induced by the cutter runout effect or the usage of mill with uneven pitch angles. To handle this issue, a unified model for chatter prediction is presented by the authors[8].

For a milling system with multiple delays, the governing equation can be expressed as the following form:

$$\mathbf{M}\ddot{\mathbf{Q}}(t)+\mathbf{C}\dot{\mathbf{Q}}(t)+\mathbf{K}\mathbf{Q}(t)=\mathbf{F}(t) \tag{12}$$

with

$$\mathbf{F}(t)=\begin{bmatrix} f_{\mathrm{X}}(t) \\ f_{\mathrm{Y}}(t)\end{bmatrix}=\mathbf{H}(t)\sum_{l=1}^{N_{\mathrm{m}}}\begin{bmatrix} x(t)-x(t-\tau_l) \\ y(t)-y(t-\tau_l)\end{bmatrix}$$

$$\mathbf{M}=\mathrm{diag}(m_{\mathrm{X}},m_{\mathrm{Y}})$$
$$\mathbf{C}=\mathrm{diag}(c_{\mathrm{X}},c_{\mathrm{Y}}) \qquad \mathbf{H}(t)=\begin{bmatrix} H_{\mathrm{XX}}(t) & H_{\mathrm{XY}}(t) \\ H_{\mathrm{YX}}(t) & H_{\mathrm{YY}}(t)\end{bmatrix}$$
$$\mathbf{K}=\mathrm{diag}(k_{\mathrm{X}},k_{\mathrm{Y}})$$
$$\mathbf{Q}(t)=[x(t),y(t)]^{\mathrm{T}},$$

where diag(*) represents diagonal matrix, m_a, c_a, k_a are modal mass, damping coefficient and modal stiffness in direction a ($a=\mathrm{X}$ or Y). N_{m} is the maximum number of delayed terms of the milling process. $\mathbf{H}(t)$ is directional matrix, and its detailed expression and term τ_l can be found in Ref[8].

The multiple delays effect leads to the variation of chip thickness, and for the convenience to handle the equation including the multiple delays effect, the cutter is divided into small segments along the axial direction. For each segment, the actual chip thickness should be properly calculated with the consideration of cutter runout influence on the cutting radius and pitch angle influence on determination that weather the cutter is in cut or not. Then, the SD method proposed by Insperger[7] is used to solve the governing equation after some form transformation. More details can be found in Ref[8].

3. Numerical simulation of influences of cutter runout, feed rate and helix angle on final stability lobe

In this section, numerical simulations are carried out based on the updated semi-discretization method[8] to investigate the influences of cutter runout, feed rate and helix angle on final stability lobe. According to the results of the theoretical study in the above section, the influences of cutting parameters on the stability boundary for multiple modes case are consistent with that for single mode. Therefore, the simulations are carried out only for the single mode case to save computational costs. It should be noted that, although the influence of cutting parameters on final stability lobes with multiple modes and single mode case are almost the same, the predicted lobe with single mode for multiple dominated modes system will inevitably lose its accuracy in some speed range for the ignorance of other dominated modes. To remedy this, one can refer to the LEM method[13].

The selected parameters for a 3 fluted flat end cutter of half immersion down milling case are shown in Table 1,while the predicted stability lobes are depicted in Fig.1.

Table 1. Modal parameters and cutting conditions

Modal Parameters		Modal Directions		Natural Frequency (Hz)	Damping Ratio (10^{-2})	Modal Mass (kg)
		X		851.2	2.5	0.85
		Y		883.4	2.0	0.92
Cutting conditions	*Kt* (MPa)	*Kr* (MPa)	ρ (mm)	λ (deg)	Feed (mm/ tooth)	Helix Angle (deg)
Case 1	1110	440	0	0	0.05	30
Case 2	1110	440	0.05	30	0.05	30
Case 3	1110	440	0.05	30	0.1	30
Case 4	1110	440	0.05	30	0.1	20
Case 5	1110	440	0.05	30	0.1	10

According to the simulated results, by comparing stability lobes for Case 1 and Case 2, we can find that the occurrence of cutter runout will increase the stability boundary in the concerned spindle ranges. From the comparison of Case 2 and Case 3, the conclusion that low feed per tooth can lead to larger stability region can be drawn. Besides, the stability lobes of Case 3, Case 4 and Case 5 show that the influence of helical angle on the stability lobe is quite small compared with runout offset and feed rate.

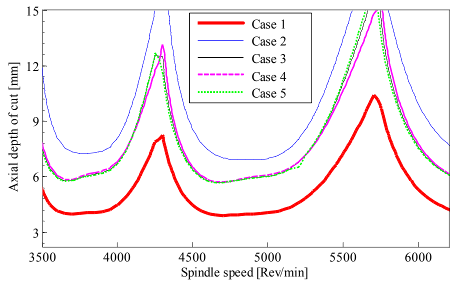

Fig.1 Simulated stability lobes

3. Experimental verification

To validate the simulated results, cutting experiments have been carried out on a vertical machine center. 3-fluted cutter with 30° helix mounted on a DEREK BT40 holder with a HAFFMAN collet chuck was used to mill an Al7050 block mounted on the table of dynamometer Kistler 9255B fixed on the machine table. Modal masses, damping ratios and stiffness constants were measured by impact modal test in two orthogonal directions. Determined modal mass, damping and stiffness coefficients are listed in Table 2. Meanwhile, cutting force coefficients and runout parameters determined from a half radial immersion down milling test are also given in Table 2. The experimental results are demonstrated in Fig.2. And both the force and sound are measured to detect chatter by spectra analysis with the aid of FFT technique. The stability lobes are calculated with improved SD method proposed in Ref.[13] for both cases of including and excluding the effect of cutter runout.

Table 2. Experimental parameters of the milling system[13]

Modal Direction	Modal No.	Natural Frequency (Hz)	Damping Ratio (10^{-2})	Modal Mass (kg)	Modal Stiffness (N/μm)
X	1	841.16	2.0907	0.1066	2.9785
X	2	1199.69	2.17	0.0482	2.7384
Y	1	854.5	4.4449	0.0707	2.0368
Y	2	1212.52	1.416	0.0558	3.2414
Cutting condition	K_t (MPa)	Kr (MPa)	ρ (μm)	λ (deg)	Feed (mm/ tooth)
	1026.6	463.63	15	15	0.05

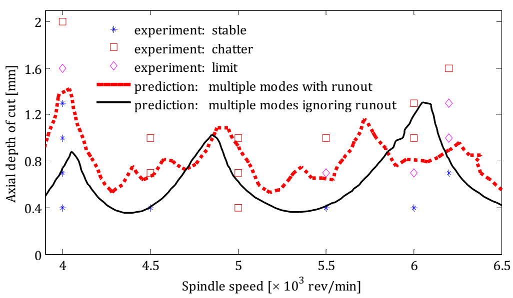

Fig.2. Experimental results and predicted lobes with runout and ignoring runout

As shown in Fig.2, the stability boundary was increased locally when cutter runout is taken into consideration, such as the spindle range from 4000 rev/min to 4600rev/min. If cutter runout is ignored, the predicted stability lobe will fail to predict in the speed around 4000 rev/min. It can also be found from Fig.2 that the predicted stability lobe with runout is in better agreement than the one ignoring runout. Therefore, considering cutter runout when predicting the stability can achieve higher accuracy. Meanwhile, the good agreement between predicted results and experimental ones demonstrates the validity of the prediction method.

4. Conclusion

In this paper, the authors have carried out numerical and experimental studies on the stability of milling process with multiple modes. And influences of the combination of cutter runout, feed rate and helix angle on final stability lobe are well investigated. The conclusions of the paper can be drawn as follows:

1. The cutting parameters on the stability lobes for multiple modes has the same influence with the single mode case, for the stability lobe with multiple modes can be approximated by the envelop of stability lobe corresponding to each single mode.
2. The occurrence of cutter runout will enhance the stability boundary locally.
3. The lower the feed rate is, the larger stability boundaries are.
4. The influence of helical angle on the stability can be neglected when considering cutter runout and feedrate.

Acknowledgements

This research has been supported by the National Natural Science Foundation of China under Grant No. 11272261, the Program for New Century Excellent Talents in University under Grant No. NCET-12-0467 and the Fundamental Research Funds for the Central Universities.

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